Understanding mesoscale organization of closed-cell marine stratocumulus

using Large-eddy simulation and observations from the ARM Eastern North Atlantic Site

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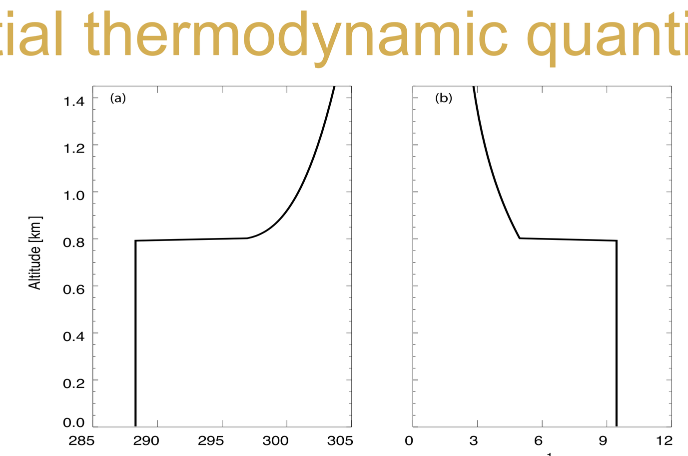
Background

- So far, there is no clear consensus about the mechanism as to mesoscale organization of stratocumulus.
- Past observational studies suggest a good correlation between mesoscale humidity and cloud water perturbations.
- Past modelling studies suggest evident feedback of moisture processes and cloud top radiative cooling on boundary-layer circulations.
- But, how does the feedback function?
- Here we frame mesoscale organization of stratocumulus as a buoyancy-driven convective instability amplifying boundary-layer humidity perturbations via cloud physics and cloud-radiation interaction combined with turbulent boundary-layer dynamics.

Large-eddy simulations (LES)

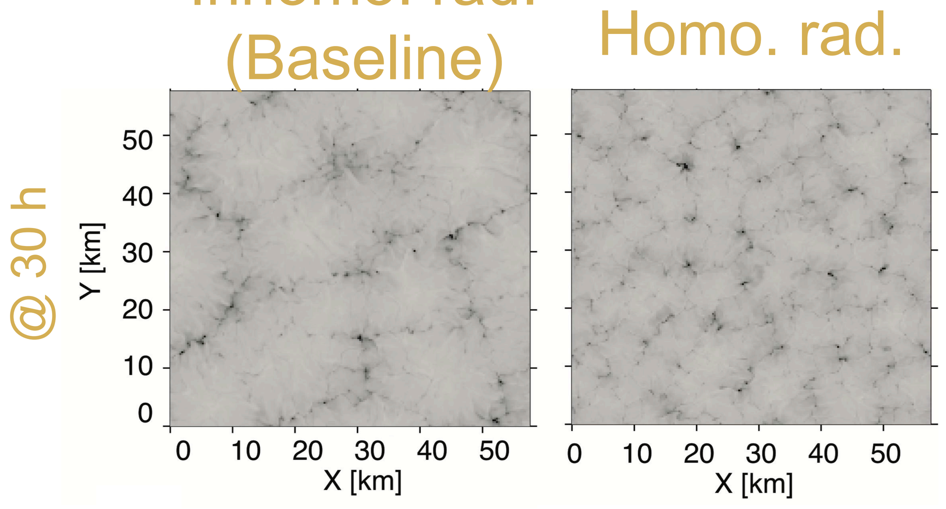
- **60 x 60 x 1.5** km grid with Dx=Dy= 300 m and predominant Dz=5 m
- 2-moment microphysics (Morrison et al. 2005) with prognostic saturation excess (Morrison and Grabowski 2008)
- Fixed cloud droplet number concentration (N_d= 500 cm^{-3}) to completely suppress drizzle
- Meteorological context: GEWEX Cloud System Study (GCSS) **DYCOMS-II** second research flight (**RF02**) model intercomparison case (Ackerman et al., 2009).
- Fixed surface fluxes; no initial horizontal wind; parameterized longwave cooling and heating.
- **Hard nudging**: **horizontal mean nudging** of θ and q_v. Time scale 600 s. Independent of altitude.

Initial thermodynamic quantities



Inhomo. rad. (Baseline) Homo. rad.

@ 30 h

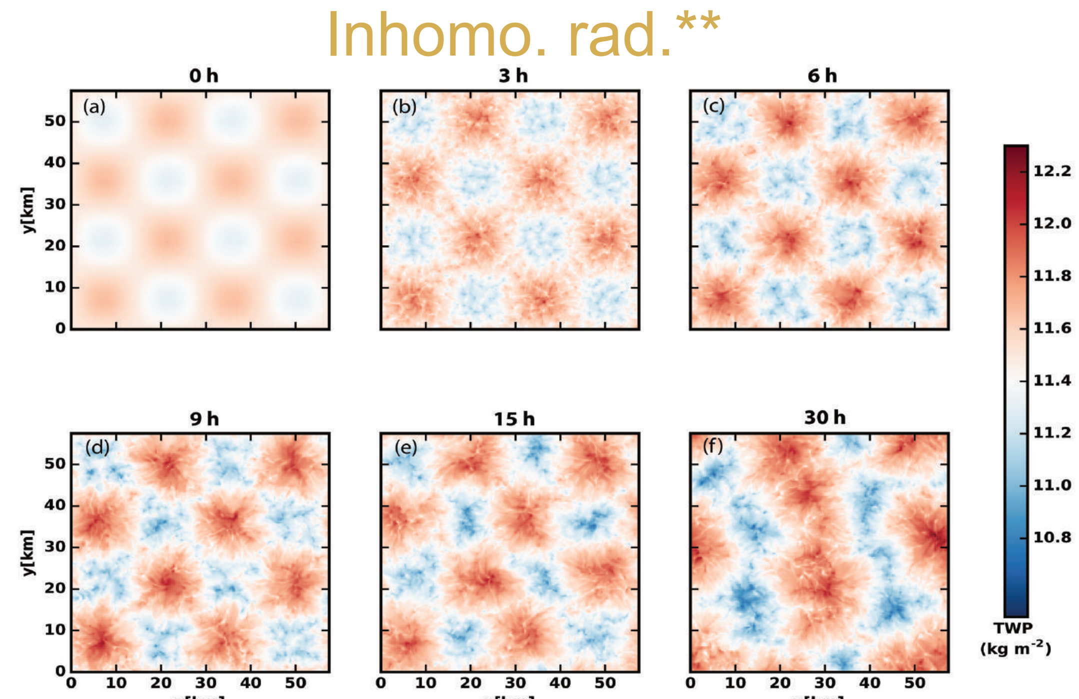


- Closed cells do not grow if radiative cooling is artificially horizontally homogenized.

A long-wavelength humidity anomaly amplifies

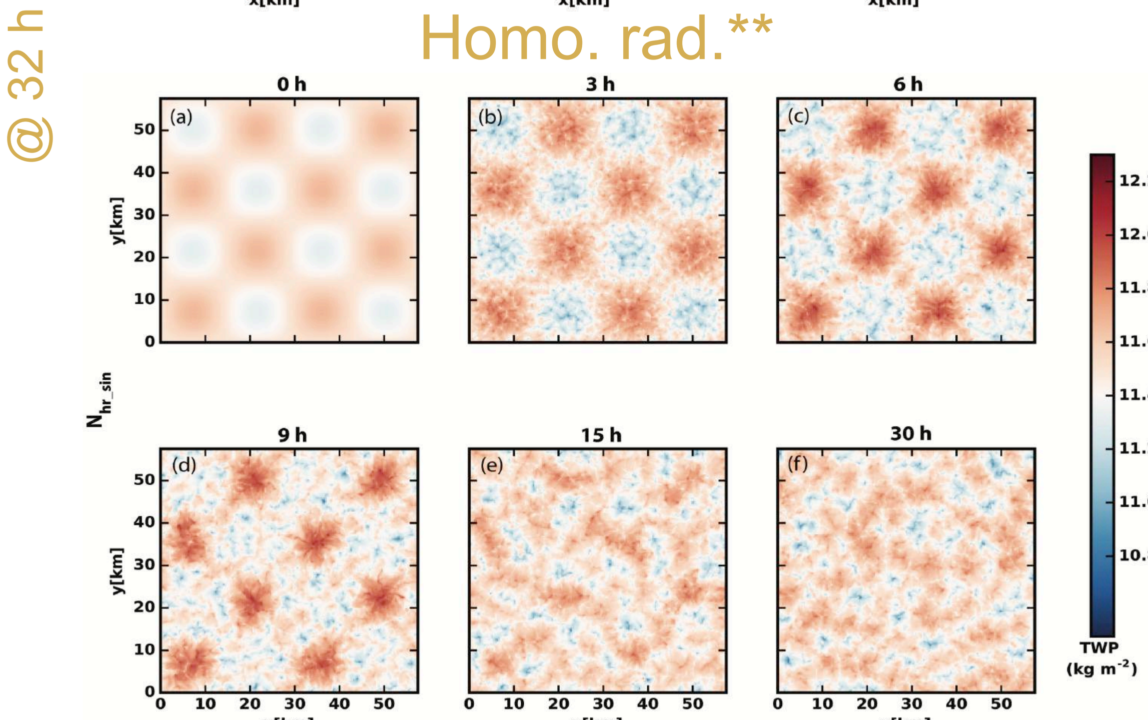
**Consider two additional simulations of baseline and homo. radiation case, initialized with a sinusoidal q_t perturbation applied uniformly across all levels in the boundary layer.

Inhomo. rad.**



Homo. rad.**

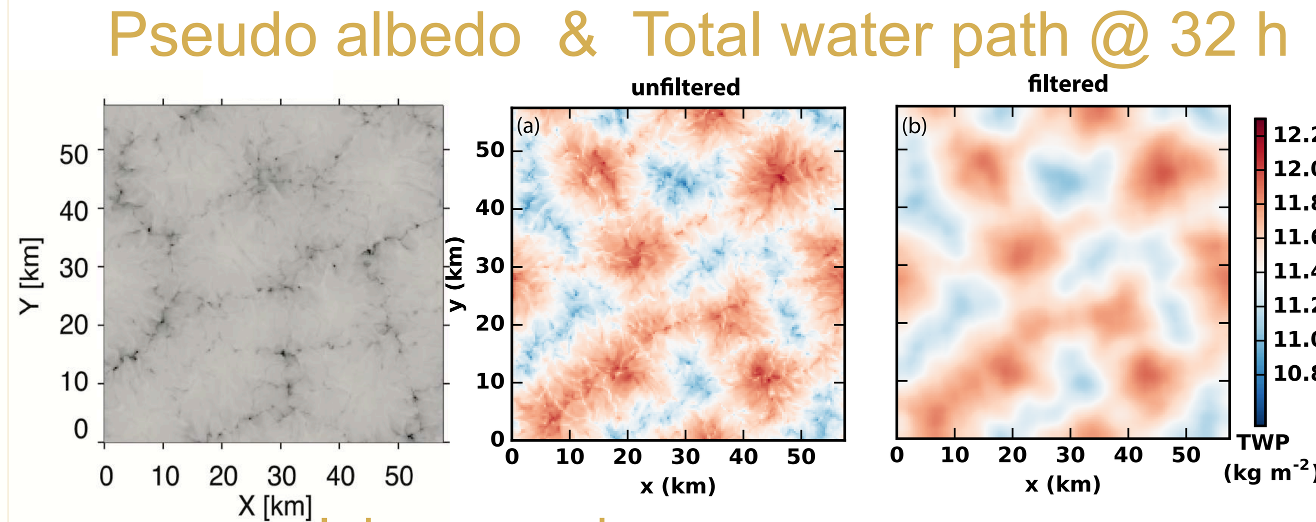
@ 32 h



- Boundary-layer circulation in the presence of inhomogeneous radiation is unstable to the development of mesoscale closed cells at large wavelength.

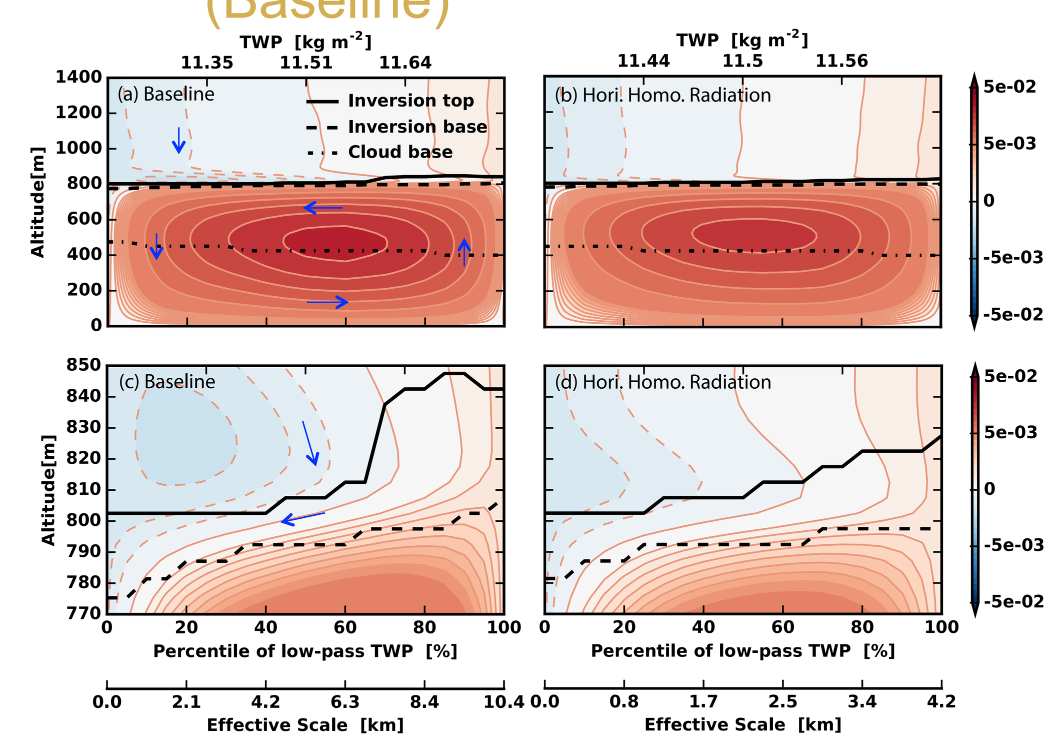
Compositing based on column-integrated humidity

Pseudo albedo & Total water path @ 32 h



Inhomo. rad. (Baseline) Homo. rad.

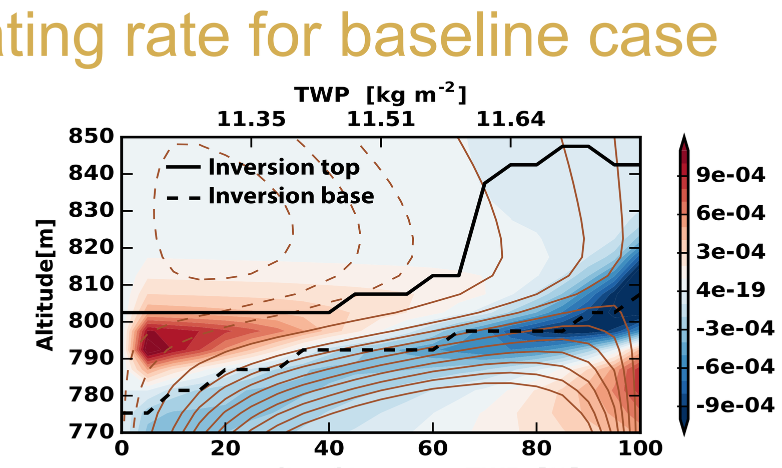
@ 32 h



- When radiative cooling is horizontally homogenized, mesoscale circulation inside PBL is reduced and PBL is flatter. The horizontal scale between dry and moist anomalies reduces to less than half as large as the baseline.

Mesoscale anomalous radiative heating rate for baseline case

@ 32 h



- Radiative cooling anomalies strongest in and just below the sloping inversion, nearly exactly followed by the streamlines——helping air slide down sloped inversion, preferentially cooling the dry columns and creating buoyancy forces that amplify the mesoscale circulation.

Mesoscale buoyancy, θ_{vl}, and latent heat variations

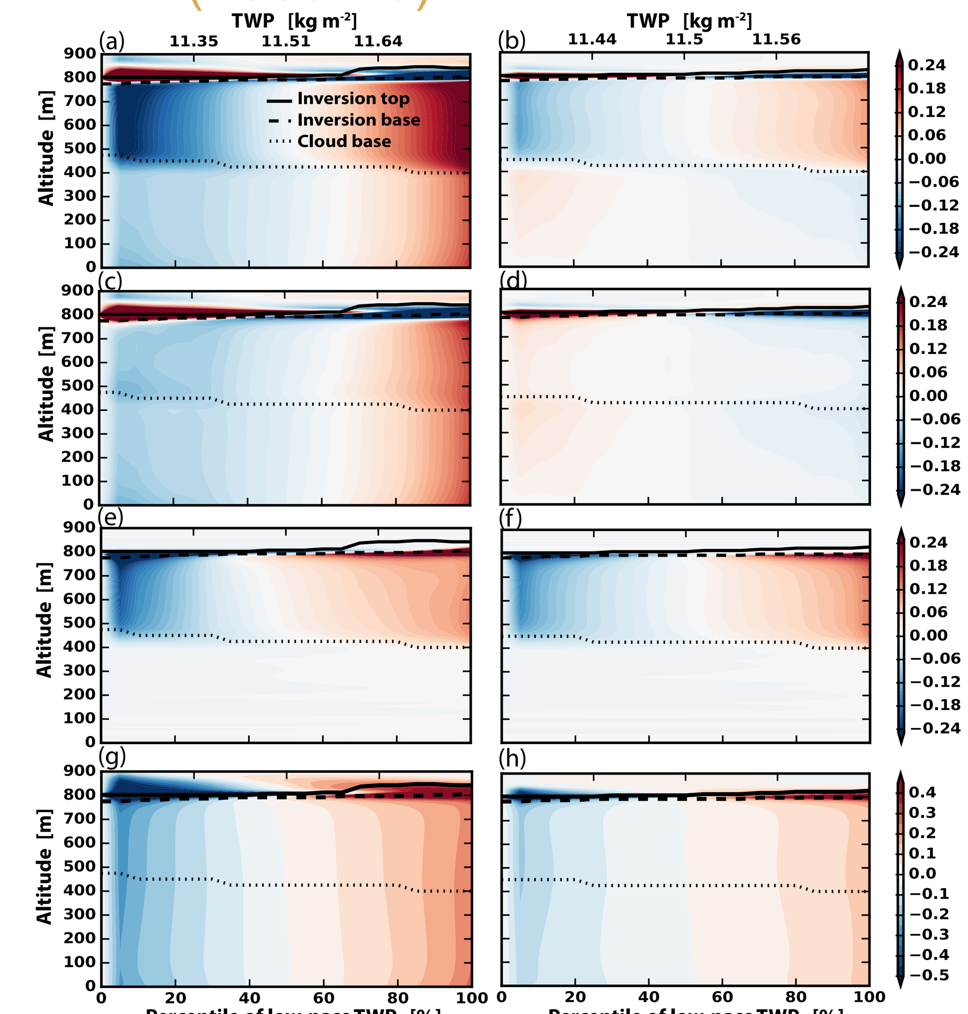
Buoy.: $\boldsymbol{\theta_v \approx \theta_{vl} + H_{LT}}$ *

Moist-conserved buoy.: $\theta_{vl} = \theta - \frac{L_v}{C_p\Pi}(q_c + q_r) + 0.608\theta_0 q_t$ †

Latent heat: $H_{LT} = \left(\frac{L_v}{C_{p}\Pi} - 1.608\theta_0\right) q_l$ Δ

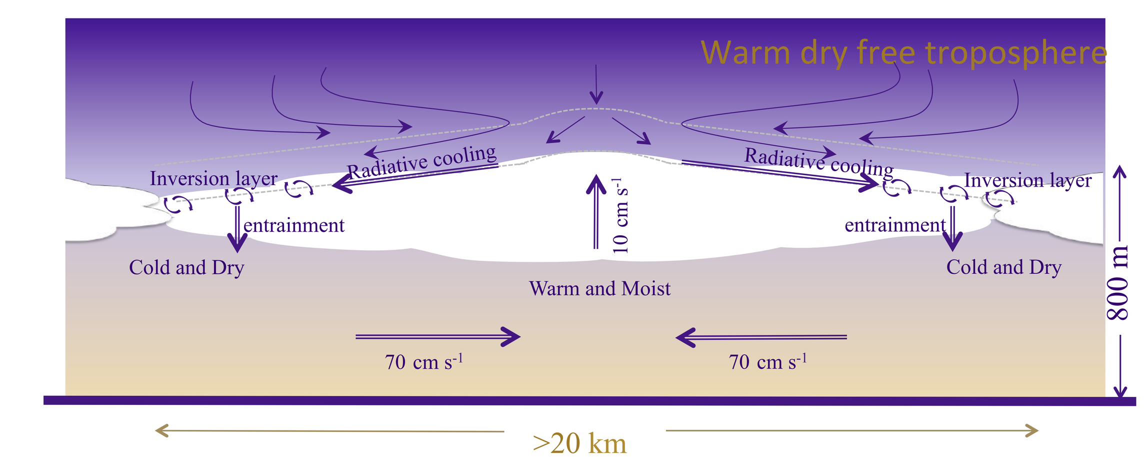
Inhomo. rad. (Baseline) Homo. rad.

@ 32 h



† Mesoscale θ_{vl} variation distribution reversed in the horizontally homogeneous radiation case, reducing mesoscale buoyancy flux and hamper the mesoscale circulation.

Composite-based schematic of closed-cell convection



Composite-based schematic of closed-cell convection

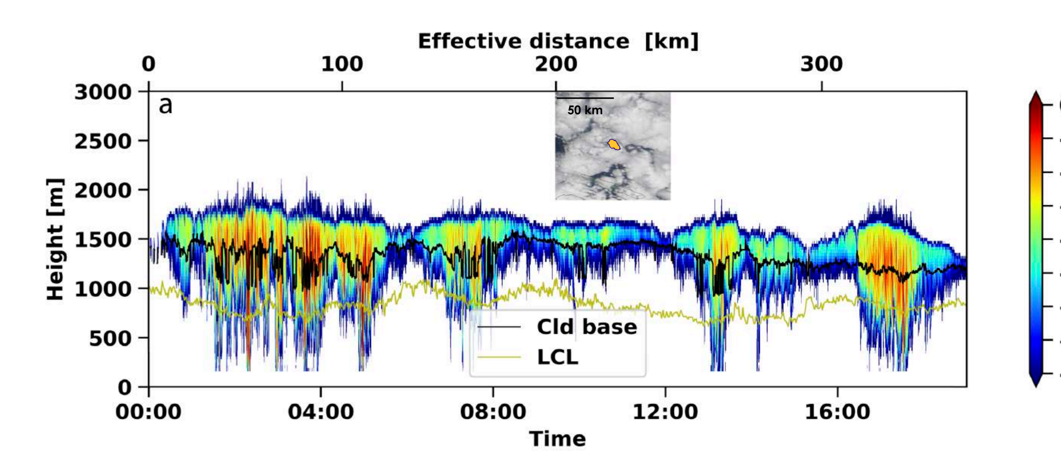
> Buoyant updrafts in moist, cloudy regions

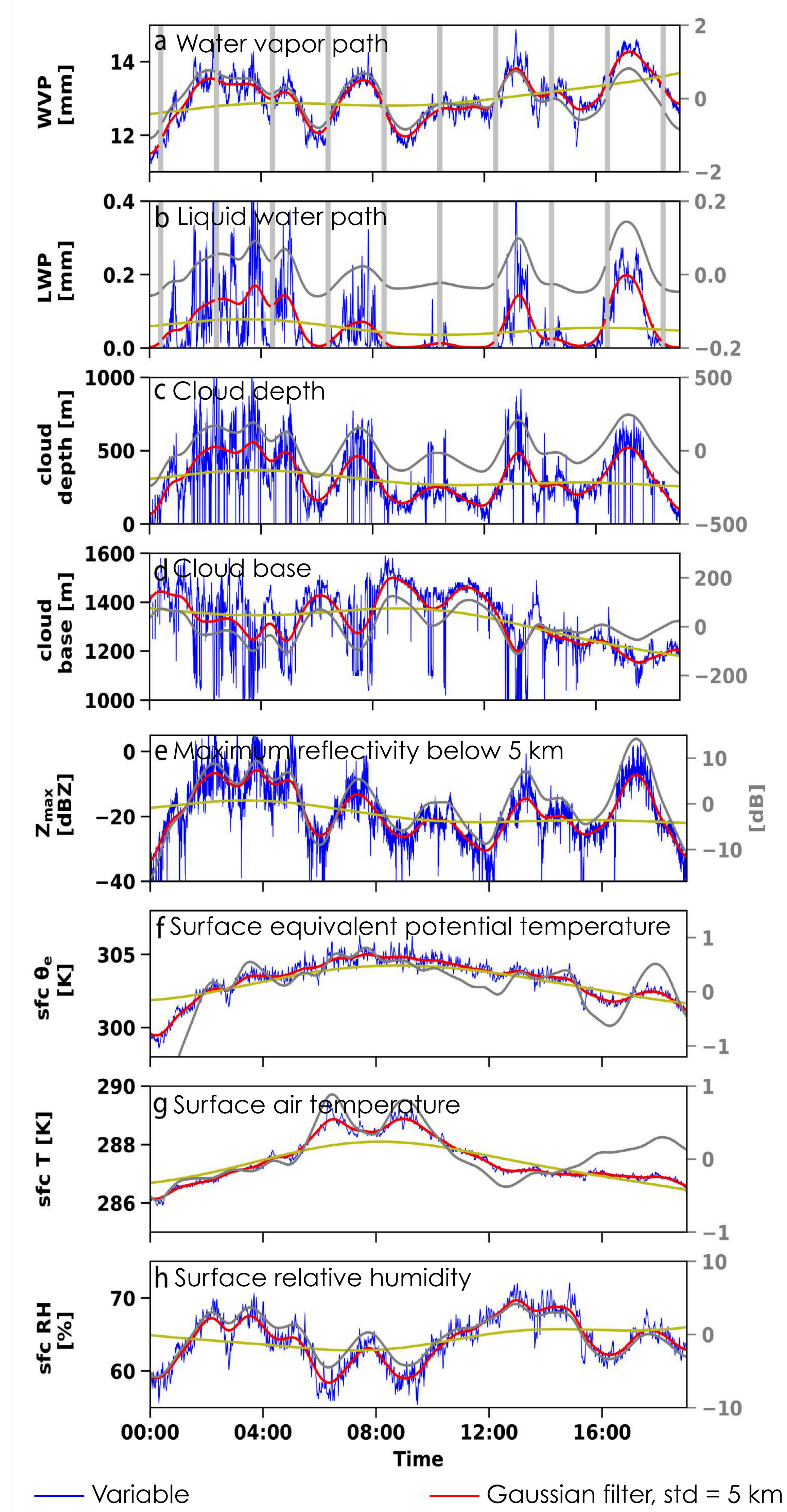
> Entrainment driven by stronger turbulence preferentially dries the dry regions

> Cloud-top radiative cooling of air sliding down inversion from moist to dry region

> Net result: Moist regions moisten and warm relative to dry regions, amplifying the humidity anomalies

Observations at ENA site





- Moister regions see thicker clouds, higher cloud tops, lower cloud bases, and stronger precipitation.
- Strong and similar correlations are found in 380 hours of closed-cell cases at the ENA site.
- Observations are consistent with the theory from LES study.

Zhou, X. & Bretherton, C. S. (2019). Simulation of Mesoscale Cellular Convection in Marine Stratocumulus: 2. Nondrizzling Conditions. *Journal of Advances in Modeling Earth Systems, 11*(1), 3-18.
Zhou, X. & Bretherton, C. S. (2019). The correlation of mesoscale humidity anomalies with mesoscale organization of marine stratocumulus from observations over the ARM Eastern North Atlantic Site. *JGR*. Submitted.

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